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Evaluation of a sonic telemetry system in three habitats of an estuarine environment

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Evaluation of a sonic telemetry system in three habitats of an estuarine environment

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Abstract

A directional sonic telemetry system in small embayment, seagrass, and channel habitats in Core Sound, North Carolina was evaluated. We compared point location estimates calculated after correcting for system bias in three different ways: using test station (i.e. known location transmitting–receiving stations) angle errors, and using a within test site and an among test site mean angle error estimate. Estimates are necessary because, when tracking an animal, system bias cannot be corrected for using test station angle errors. In addition, telemetered animals may move beyond test areas or into different habitats. We found no significant difference ($P > 0.05$) among point location estimates, suggesting that a within or an among mean angle error was an acceptable estimate. Choosing the appropriate angle error estimate must be done carefully because both presented limitations. A within test site mean angle error was the more conservative approach, avoiding biases caused by significant ($P < 0.05$) interhabitat angle error variability. An estimate containing interhabitat variability (i.e. among test site angle error) might be more robust for correcting system bias when the instrumented animal moves outside test areas or into a heterogeneous area. Seagrass habitat polygons in southern Core Sound range in size from 0.1 to 3189 ha. Attained levels of accuracy and precision from this study suggest that work could be conducted in areas where polygons are ≥ 6.9 ha, which represents $> 97\%$ of the seagrass habitat in Core Sound. Although the majority (80%) of the polygons are small (< 10.0 ha), they represent $< 5\%$ of the total seagrass area. In addition, classifying use of habitat in areas where polygons are ≤ 6.9 ha is possible because small polygons have a contagious distribution; hence, their areas may be additive. Risks of misclassifying use of habitat can be reduced also by controlling the size of confidence areas (A_e) by adjusting the distance between observers and the tracked animal. The confidence area as a function of distance can be predicted because location error varied linearly and significantly with geometric mean distance (D_g). On the basis of this relationship, D_g must be < 326 m for $A_e 95$ to be < 10.0 ha. © 1997 Elsevier Science B.V.

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1. Introduction

The importance of estuarine areas to sea turtles, especially during the critical immature life history stages, has been documented (Mendonça and Ehrhart, 1982; Ehrhart, 1983; Mendonça, 1983; Lutcavage and Musick, 1985; Keinath et al., 1987; Burke et al., 1993; Morreale et al., 1992; Epperly et al., 1995a,b). Radio telemetry has been one method used to study sea turtle movement and use of habitat (Ogden et al., 1983; Byles, 1988). Collazo and Epperly (1995) noted that the main advantage of using radio telemetry in sea turtle studies was the greater range of signal detection. This advantage, however, could be nullified by radio telemetry's dependence on the frequency and duration of surfacing events, signal attenuation in salt water environments, and the assumption that surface locations are directly above used habitat (see Winter, 1983; Collazo and Epperly, 1995). Directional sonic telemetry avoids these problems, albeit at shorter ranges. The main advantage of this technique is the ability of observers to continuously track telemetered individuals (Collazo and Epperly, 1995).

The usefulness of movement and habitat use data in telemetric studies depends on the accuracy and precision of location (i.e. position) estimates (White and Garrott, 1990). Biased location estimates result because environmental (e.g. bottom contour, water depth, submerged vegetation for sonic systems) and logistical (observers, equipment) factors (Winter, 1983; Collazo and Epperly, 1995) can affect the fundamental data used to calculate them—the angle error (i.e. the deviation from the true bearing)(White and Garrott, 1990). It becomes necessary, therefore, that telemetry studies, including those using directional sonic telemetry, be preceded by accuracy and precision assessments to correct for any system bias before estimating an animal's location (White and Garrott, 1990; Collazo and Epperly, 1995; Zimmerman and Powell, 1995).

Collazo and Epperly (1995) evaluated the appropriateness of a directional sonic telemetry system for conducting studies of sea turtle use of habitats in Core Sound, North Carolina. They suggested that levels of accuracy and precision in assigning turtles to habitat types were adequate for areas where habitat polygons were larger than 8.26 ha. However, their study was conducted in a single habitat, a channel. In Core Sound, an estuarine lagoon, three major habitat types have been recognized: channels, expansive shoals with seagrass meadows behind the barrier islands, and shallow embayments with small seagrass habitat polygons along the mainland shore (Ferguson et al., 1993). Sea turtles have been sighted in all of these habitats (Epperly et al., 1995a,b). The likelihood that turtles move outside test areas and across habitats raises two important issues with regard to experimental design and execution of habitat use and movement studies. First, as indicated above, environmental factors can affect angle errors. Second, when tracking an instrumented animal, system bias cannot be corrected for using individual test station angle errors (i.e. fixed, known reference station). This becomes more evident if the animal moves outside test areas. An estimate of mean angle error within or among test areas must be used instead.

Here we report on accuracy and precision tests conducted in each of the three major habitats of Core Sound. We also discuss the tradeoffs of using an intra- or interhabitat estimate of angle error to estimate point locations. For such assessment, we compared point locations estimated, after correcting for system bias, in three ways: 1) using mean angle errors obtained from test stations (known location transmitting–receiving stations), 2) using a mean angle error from each test area (hereafter, within site mean angle error), and 3) using a mean angle error from all sites combined (hereafter, among site mean angle error). In habitat-use studies, misclassification errors can be reduced by selecting a distance interval between instrumented animals and observers that maximizes accuracy and precision but at the same time does not affect the behavior of the animal and minimizes the need to reposition observers each time the turtle moves (Collazo and Epperly, 1995). Thus, we also examined the relationship between geometric mean distance (D_g) and location error (E) using pooled data from this study and Collazo and Epperly (1995).

2. Materials and methods

We set up transmitting–receiving stations in embayment, channel, and seagrass test sites using existing navigation markers or polyvinyl chloride (PVC) pipe in Core and Back Sounds (Fig. 1). Four stations were set up in embayment, seven in channel, and six in seagrass test sites. Stations were positioned far enough away from one another to maximize the area surveyed, but were still close enough to each other to allow for signal reception (Table 1).

To obtain each station's geographic location, 40 Differential Global Positioning System (DGPS) (Trimble Navigation Ltd., Sunnyvale, CA, GPS Pathfinder Basic) readings were collected over a 10 min period at each station, differentially corrected to improve accuracy of the position estimate using a nearby reference site (<20 km) located at the National Marine Fisheries Service Beaufort Laboratory, Beaufort, N.C., and averaged. Use of DGPS is not considered a significant source of error in location estimates (Collazo and Epperly, 1995). Using basic trigonometric formulas, we calculated the true angle from each receiving station to each transmitter station and the distances between stations.

VEMCO, Inc. (Nova Scotia, Canada) high-power sonic transmitters (50.0 kHz model V3-4H), a directional linear array hydrophone (model V-10), and a receiver (model V-60) were used during data collection. The hydrophone and a digital compass (Azimuth 1000, KVH Industries, Inc., Middletown, R.I.) were mounted at each end of a 1.2-m long PVC pipe and aligned visually. Transmitters were attached to stations at mid-depth to simulate a transmitter attached to a submerged, swimming sea turtle.

We collected 30 magnetic bearings, recorded to the nearest degree, from each transmitting–receiving station combination using the "loudest signal" technique (Springer, 1979). We recorded compass readings without observer knowledge of the true bearing or hydrophone orientation, and removed the hydrophone from the water between readings (Collazo and Epperly, 1995). We used only one observer throughout the

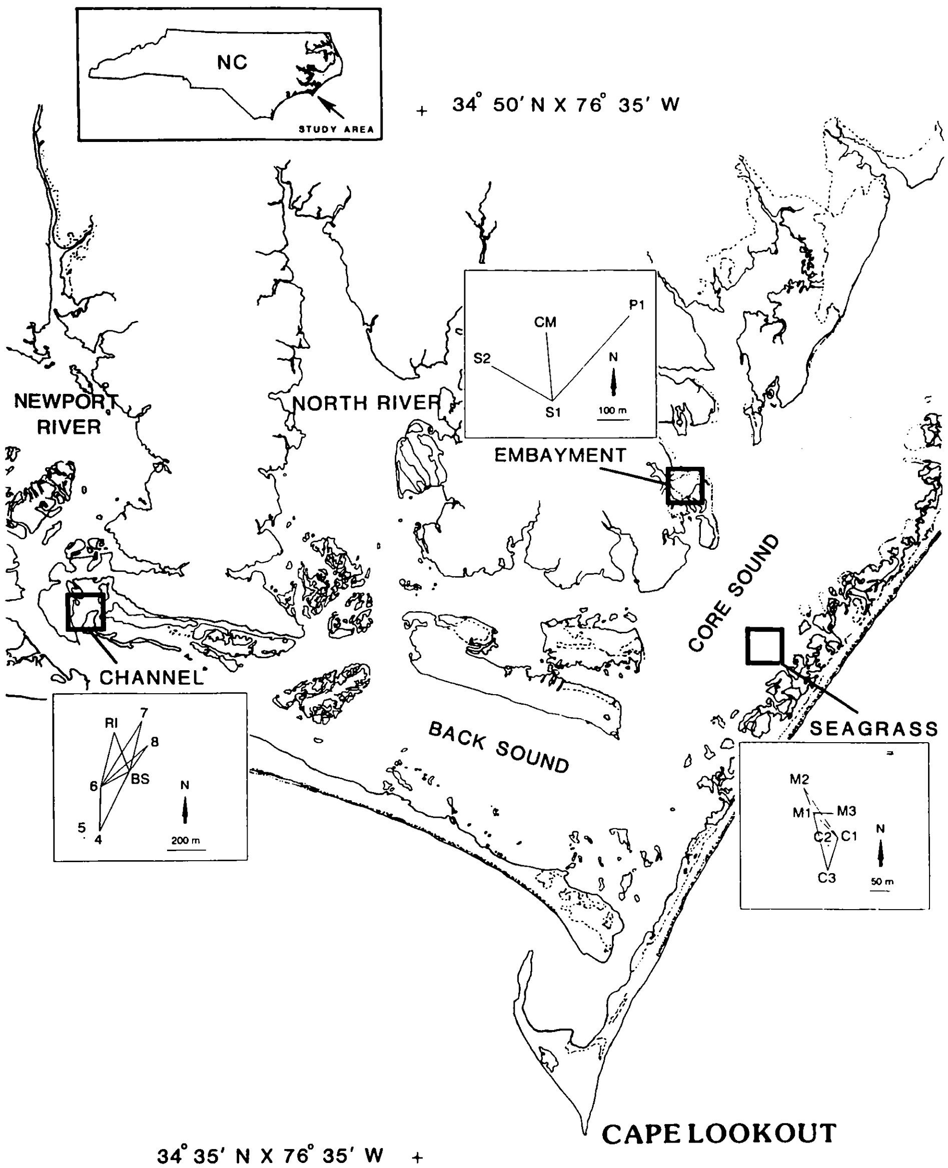

Fig. 1. Embayment, channel, and seagrass test sites with transmitting–receiving station configurations for estuarine study area, North Carolina.

experiment. All readings were recorded from a site within three consecutive days. Data were collected on 11–29 August 1993.

We assessed angle errors to determine and correct for system bias, if necessary, prior to estimating point locations (Springer, 1979; Lee et al., 1985; White and Garrott, 1990;

Table 1
Angle errors (in degrees) obtained from 20 transmitting (T)–receiving (R) stations of embayment, channel, and seagrass test sites using sonic telemetry in an estuarine environment, North Carolina ($n = 30$/combination[a]).

Test site	Station combination T to R	Distance (m)	Depth between stations z	Depth between stations SD	True bearing	Angle Error Bias ($\bar{e}$)	Angle Error Precision (SD)
Embayment	P1 to S1	350	0.6	0.0[b]	221°	−13°	5
	S2 to S1	212	0.7	0.0[b]	120°	−14°	5
	CM to S1	211	0.7	0.0[b]	175°	−13°	5
	S1 to CM	211	0.7	0.0[b]	355°	−14°	8
	Overall	–	0.6	0.1	–	−14°	6
Channel	7 to 6	404	5.3	1.2	211°	−16°	7
	8 to 6	319	2.9	0.7	227°	−13°	10
	RI to 6	294	5.1	1.1	194°	−15°	7
	4 to 6	233	3.1	0.4	2°	−10°	7
	BS to 6	163	2.3	0.7	241°	−19°	9
	6 to BS	163	2.3	0.7	61°	−19°	9
	RI to BS	220	4.2	2.1	161°	−18°	8
	7 to BS	275	3.9	2.1	194°	−13°	6
	8 to BS	165	2.0	0.7	214°	−15°	6
	4 to BS	345	1.9	0.7	25°	−14°	5
	Overall	–	3.6	1.7	–	−15°	8
Seagrass	C3 to C1	64	1.0	0.0[b]	17°	−14°	5
	M2 to C1	112	1.0	0.1	146°	−15°	6
	M1 to C1	64	1.1	0.0[b]	136°	−17°	6
	M2 to M1	50	0.9	0.2	159°	−13°	6
	C3 to M1	110	1.0	0.1	347°	−11°	4
	M3 to M1	38	0.9	0.0[b]	272°	−16°	5
	Overall	–	1.0	0.1	–	−14°	6

[a]An outlier in Channel combination 6 to BS was excluded from analysis.
[b]SD<0.05

Collazo and Epperly, 1995). Angle error was calculated by subtracting the true bearing from each observed bearing after correcting for magnetic deviation and hydrophone/compass alignment error. These angular differences never exceeded 180°, thus linear statistics were employed (Batschelet, 1981). The data met assumptions of normality. *T*-tests were used to determine if the distribution of mean angle errors varied significantly from zero. We tested for differences in transmitting–receiving station combination mean angle errors both within and among test sites using a random effects ANOVA.

Location estimates were obtained from the triangulation of two bearings whose angle of intersection was between 45° and 135° (Springer, 1979). Test station angle errors and within and among test site mean angle errors were used to correct for bias. We calculated location estimates using Lenth's maximum likelihood estimator (White and Garrott, 1984), and utilized Zimmerman and Powell (1995) location error method to report measures of accuracy and precision. Median location error (E_m), the median value of the 30 linear distances between known and estimated locations, represented estimated location accuracy. Confidence levels (precision) for the estimated locations of test transmitters were expressed as the distances that contained 90% and 95% of the values. Confidence areas (A_e) around the location estimates were generated using the respective confidence distance as the radius of a circle (Zimmerman and Powell, 1995). Geometric mean distance (D_g), a measure of distance relating the distances from 2 receivers (x_1, y_1 and x_2, y_2) to the transmitter (x, y), was calculated as $\sqrt{d_1 \cdot d_2}$ where

$$d_1 = \sqrt{(x - x_1)^2 + (y - y_1)^2} \text{ and } d_2 = \sqrt{(x - x_2)^2 + (y - y_2)^2}$$

(Zimmerman, 1990). We tested whether E obtained using the 3 different estimates of angle error were different using a Kruskal–Wallis test. We re-analyzed Collazo and Epperly (1995) data, correcting for system bias using their within mean angle error (Collazo and Epperly reported their results using test station angle errors), and combined them with ours to examine the effect of D_g on E_m and 95th percentile location error (E_{95}), using a simple linear regression model (Hupp and Ratti, 1983; Zimmerman, 1990; Zimmerman and Powell, 1995).

Water depth may affect angle error (Winter, 1983). For this reason, we worked in areas of uniform water depth, which are fairly characteristic of North Carolina lagoons. To document existing variability, we mapped depth profiles for all station combinations using a Lowrance X-16 sonar and verified depth at each station. We divided embayment and channel bottom profiles into 25 m increments and seagrass bottom profiles into 0.5 m increments. Incremental depth readings were used to determine range and average depth ($\bar{z}$) $\pm$ standard deviation (SD) for each study site.

3. Results

3.1. Embayment

All four stations were used to estimate angle errors (Fig. 1). Mean angle errors differed significantly from zero ($t = -25.47$; df$=119$; $P<0.001$), but test station mean angle errors were not significantly different from each other ($F=0.44$; 3 116 df; $P=0.72$) (Table 1). Water depth within the test site was relatively uniform (CV=9.5%), and ranged from 0.6 to 0.8 m.

We obtained 90 location estimates from paired angles whose angles of intersection ranged from 46° to 101°, after correcting for bias. S1 served as the transmitting station for estimating location errors. Estimated location errors using test station angle errors ranged from 9.2 to 197.7 m; estimated location errors using a within test site mean angle error ranged from 7.1 to 189.5 m; and estimated location errors using an among test site mean angle error ranged from 4.4 to 195.0 m (Table 2). The E_{95}s generated using the 3 different estimates of angle error were not significantly different from each other ($\chi^2=0.62$; df$=2$; $P=0.73$).

Table 2
Geometric mean distance (D_g) and median location error (E_m) in meters, and associated confidence areas (A_e) in hectares at the 50%, 90%, and 95% level for each transmitting (T) and pair of receiving (R–R) station combinations obtained using sonic telemetry in embayment, channel, and seagrass test sites in an estuarine environment, North Carolina. Data after test station angle error and within and among site mean angle error bias corrections, respectively, are reported for each test site.

Test site	n^a	D_g	E_m	Confidence Areas		
				A_e50	A_e90	A_e95
Embayment	90	211.6–272.6	47.7	0.7	4.0	4.5
			47.4	0.7	3.8	4.8
			53.7	0.9	4.2	5.3
Channel	148[b]	188.9–275.3	50.2	0.8	6.1	10.7
			45.6	0.7	4.4	6.7
			44.2	0.6	4.6	6.9
Seagrass	120	43.5–84.6	14.1	0.1	0.5	0.7
			14.9	0.1	0.5	0.7
			15.2	0.1	0.5	0.7

[a]Number of T to R–R station combinations with bearing intersections of 45° to 135°.
[b]An outlier from channel combination 6 to BS was excluded from analysis.

3.2. Channel

Markers 6 and BS served as transmitting stations and angles were recorded from all stations except navigation marker 5, where signals were not strong enough to take angles (Fig. 1). Also, a reading from test station combination BS-6 was excluded. This reading was, on average, 90° greater than all other readings, and thus considered an outlier. Mean angle errors differed significantly from zero ($t = -32.82$; df=298; $P<0.001$). Mean angle errors for each test station combination differed significantly from each other ($F = 4.06$; 9 289 df; $P<0.001$) but did not exhibit a linear trend with distance (Table 1). Water depth within the test site was variable (CV=54.5%) and ranged from 0.8 to 10.4 m.

We obtained 118 location estimates from paired angles whose angles of intersection ranged from 47° to 133°, after correcting for bias. Estimated location errors using test station angle errors ranged from 2.1 to 218.3 m; estimated location errors using a within test site mean angle error ranged from 7.1 to 188.4 m; and estimated location errors using an among test site mean angle error ranged from 5.2 to 183.2 m (Table 2). The E_{95}s generated using the 3 different estimates of angle error were not significantly different from each other ($\chi^2 = 1.04$; df=2; $P = 0.60$).

3.3. Seagrass

C1 and M1 served as transmitting stations for angle and location error estimations (Fig. 1). All stations, excluding C1 and C2, were used as receiving stations. Mean angle errors differed significantly from zero ($t = -33.73$; df=179; $P<0.001$). Mean angle errors for each test station combination differed significantly from each other ($F = 4.56$; 5,174 df; $P<0.001$) but did not exhibit a linear trend with distance (Table 1). Water depth within the test site was relatively uniform (CV=15.7%) and ranged from 0.4 to 1.2 m.

We obtained 120 location estimates from paired angles whose angles of intersection ranged from 74° to 130°, after correcting for bias. Estimated location errors using test station angle errors ranged from 0.7 to 51.3 m; estimated location errors using a within test site mean angle error ranged from 0.8 to 51.6 m; and estimated location errors using an among test site mean angle error ranged from 0.2 to 52.3 m (Table 2). The E_{95}s generated using the 3 different estimates of angle error were not significantly different from each other ($\chi^2=0.62$; df=2; $P=0.74$).

3.4. Among test sites and E by D_g assessments

Test station mean angle errors varied significantly among test sites ($F=3.60$; 19 579 df; $P<0.001$) but did not exhibit a linear relationship with distance (Table 1). Estimated location error varied significantly with D_g for E_m, whether it was calculated using a within or among test site mean angle error. Including Collazo and Epperly (1995) data did not affect this relationship for E_m ($F=4.19$; df=1; $P=0.05$) and E_{95} ($F=0.13$; df=1; $P=0.72$). Differences in slope using within or among test site mean angle errors were not significantly different for E_m ($F=0.10$; df=1; $P=0.76$) and E_{95} ($F=0.02$; df=1; $P=0.89$). Fig. 2 depicts the relationship using an among test site mean angle error for E_m ($F=143.29$; 1, 11 df; $P<0.001$) and E_{95} ($F=81.88$; 1, 11 df; $P<0.001$).

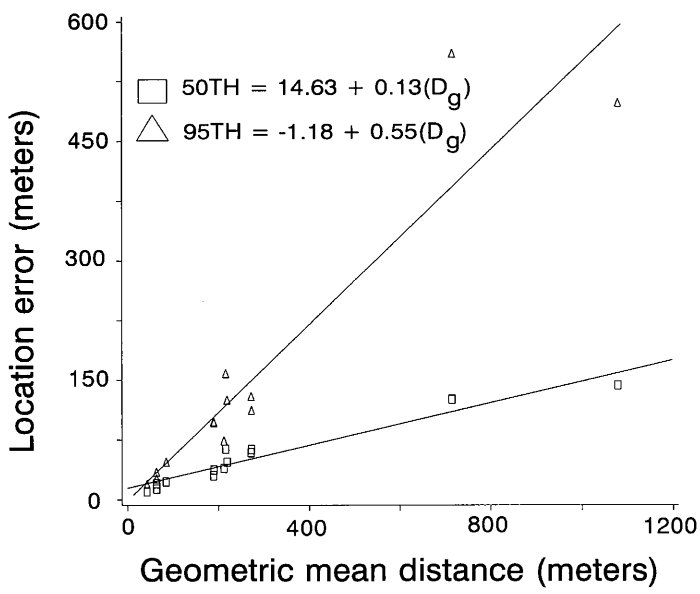

Fig. 2. Relationship between median (50th percentile) and 95th percentile location errors and geometric mean distance (D_g) for embayment, channel, and seagrass sites within estuarine study area, North Carolina. Relationship was significant for both median ($F=143.29$; 1,11 df; $P<0.001$) and 95th percentile ($F=81.88$; 1,11 df; $P<0.001$) location errors. Location errors were estimated using an among test site mean angle error.

4. Discussion

Telemetry system tests are necessary to correct for possible system bias before estimating point locations (White and Garrott, 1990; Collazo and Epperly, 1995). We corrected for system bias using test station angle error (i.e. known location transmitting–receiving stations), and within and among test site mean angle error estimates. Estimated location errors (i.e. E_{95}s) produced were not significantly different, suggesting that a within or among mean angle error is an acceptable estimate for our test sites. Choosing an appropriate angle error estimate must be done carefully, weighing statistical, as well as biological, considerations. In our study, both within and among test site angle error estimates presented limitations. Test station mean angle errors varied significantly within channel and seagrass sites, but not within the embayment site. Angle errors, however, did not exhibit a linear relationship with distance, agreeing with findings reported by Collazo and Epperly (1995) for a channel site. This lack of a linear relationship with distance minimized the need to correct for bias at every distance interval and probably contributed to the similarity we found between E using test station angle errors and within site mean angle errors. It enabled us also to describe the relationship between D_g and E.

We also found that mean angle errors differed among test sites, and were greatest in the channel test site. Location error estimates using an among site mean angle error were, as expected, biased low for channel and biased high for embayment and seagrass sites. It could be argued, then, that a within test site angle error estimate is probably a more conservative approach for correcting bias because an among site estimate might introduce another source of bias. We suggest, however, that under some circumstances, using an among test site mean angle error might be advantageous. In Core Sound, as possibly in other estuaries, there were limits to our ability to replicate system tests by distance intervals or habitats. Moreover, instrumented animals are likely to move outside test areas or are likely to be caught, tagged and released outside test areas but within the habitat of interest. It also is possible that animals may move to areas where the habitat is not homogeneous. In these cases, an among test site mean angle error could be a more accurate estimate to correct for bias because it incorporates interhabitat variability. Small biases might be offset by the potential benefit of using an angle error estimate suitable for work in non-test areas, primarily those comprising habitat mosaics. In our study, we showed that those biases did not result in significantly different location estimates. Irrespective of the angle error estimate chosen, the reader is cautioned to restrict inferences about E to within the range of distances per test site used to develop angle error estimates and the resultant relationship between E and distance. In Core Sound, this is particularly the case for our seagrass test site, where the range of sampled distances was much smaller than in the other two test sites. Reported distance ranges, however, reflect expected field conditions.

The velocity of sound through water changes as temperature, salinity or depth changes, resulting in a change in range and in a refraction or bending of sound rays in stratified bodies of water (Weihaupt, 1979; Brumbaugh, 1980). Angle errors could be affected by one or a combination of these factors. In this study, however, we emphasized the effects of distance and habitat types. Water depth was not deemed as important because Core Sound and adjacent estuarine waters are shallow (average depth 3–4 m). We documented some variability in water depth among test sites, but it did not appear to affect E. Depth was fairly uniform in the embayment (CV=9.5%) and seagrass (CV=15.7%) sites and most variable in the channel site (CV=54.5%), yet all three sites had similar E. We also know that there are insignificant differences in temperature and salinity between surface and bottom (Roelofs and Bumpus, 1953). Thus, we consider the described linear relationship between E and D_g in shallow waters of Core Sound reliable.

Seagrass habitat polygons in southern Core Sound range in size from 0.1 to 3189.0 ha (Ferguson et al., 1992), and the majority (80%) of them are small (<10.0 ha). Although small polygons comprise only 5% of the total seagrass coverage, work in such areas could limit our ability to test for use of habitat (see also Collazo and Epperly, 1995). Attained levels of accuracy and precision from this study suggest that the telemetry system described could be implemented in areas where polygons are ≥6.9 ha (Table 2) which represent >97% of the seagrass habitat in Core Sound. In addition, the telemetry system may work in some areas where polygons are <6.9 ha. Small seagrass habitat polygons have a contagious distribution (Ferguson, pers. comm.) and thus, their areas may be additive, minimizing the risk of misclassifying use of habitat. Further, risks of misclassifications can be reduced by controlling the size of A_e, achieved by adjusting the distance between observers and the tracked animal. The relationship between E_{95} and D_g developed in this study suggests that D_g must be <326 m for A_e95 to be <10.0 ha. The findings of this study are an improvement over Collazo and Epperly (1995), because we can select a D_g to meet A_e field constraints (e.g. habitat polygon size) using an appropriate estimate of angle error.

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